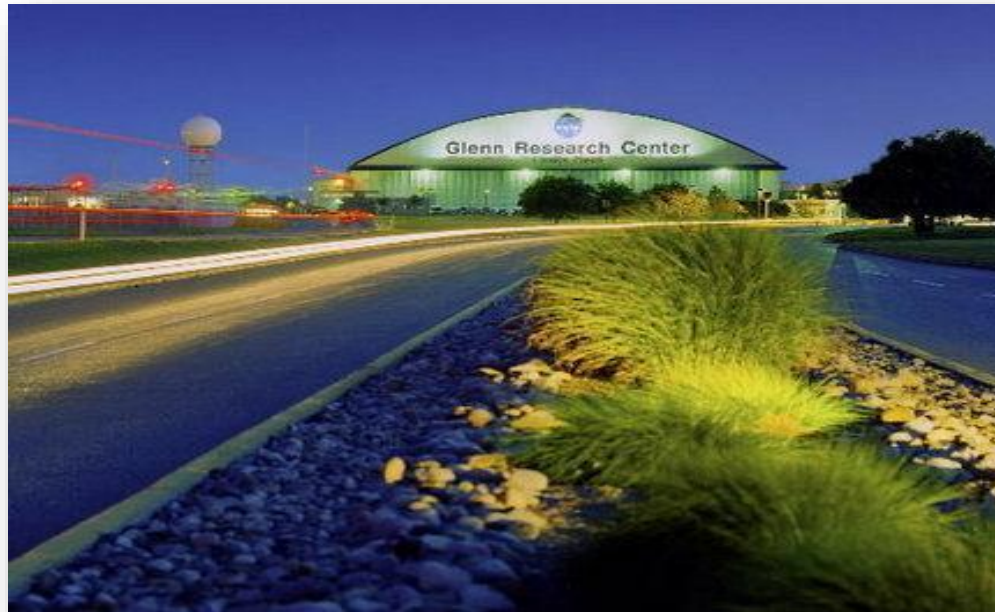




DEVELOPMENT OF SHAPE MEMORY ALLOYS- CHALLENGES AND SOLUTIONS



Othmane Benafan– NASA Glenn
High Temperature & Smart Alloys Branch
Materials and Structures Division

Presentation for: The Boeing Company, Berkeley, MO
Sept. 09, 2016





Our Goals – Materials, **Infrastructure**, **Applications**

- **Materials:**

- Develop new shape memory alloys ranging from cryogenic to high temperature for use in adaptive structures, and lightweight, solid-state actuation systems .
- Adjust material properties through alloying, processing, and thermo mechanical understanding.
- Identify methods to establish good stability, durability, workability, and work output amongst others

- **Infrastructure:**

- Develop laboratory testing capability and methods to evaluate and characterize SMA properties/ performance.
- Generate material(s) data sheets and databases
- Determine test standards/methodologies
- Component or subcomponent testing/modeling

- **Applications:**

- Identify/build applications to benefit the aeronautics and space design challenges
- Design methodologies
- Commercialization



Our Goals – Materials, Infrastructure, Applications

- **Materials:**

- Develop new shape memory in adaptive structures, and 1
- Adjust material properties to understanding.
- Identify methods to establish amongst others

- **Infrastructure:**

- Develop laboratory testing of properties/ performance.
- Generate material(s) data sheets
- Determine test standards/methods
- Component or subcomponent

- **Applications:**

- Identify/build applications to
- Design methodologies
- Commercialization

Design “**The**” material

Design “***WITH***” material

SMA Labs: Thermomechanical Testing

Cold Temperature Testing



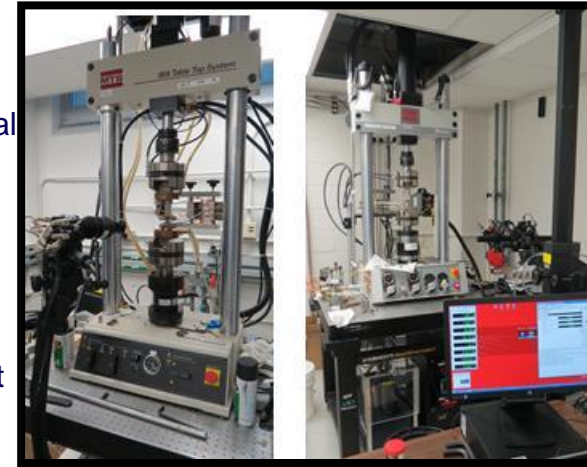
Capabilities:

- 5-22 kip load capacity
- Temperature: -125 °C to 500 °C
- Servohydraulic & electromechanical
- Load, stroke, strain control
- Tension and compression

Capabilities:

- Axial-Torsion loading
- Optical strain measurement
- Temperature > 600 °C
- Torque rating : 220 N-m
- Force rating: 22 kN

Multiaxial Testing

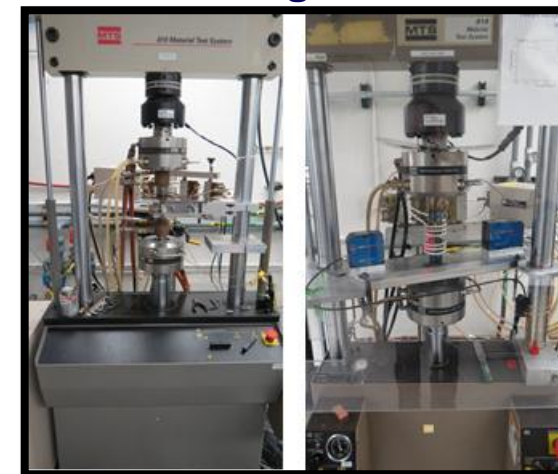


Durability Testing

- Uniaxial loading (tensile loading)
- Torsion (torque tubes)
- Fast cycling times (5 minutes cycle)



Uniaxial High Temperature Testing



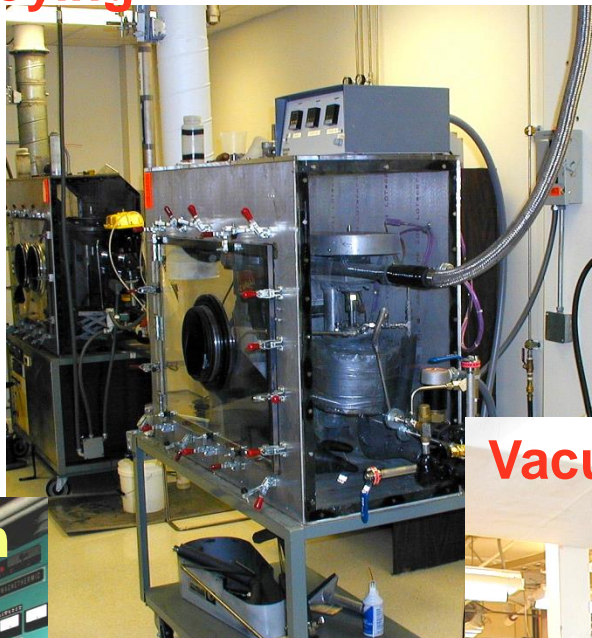
Capabilities:

- Laser strain measurement
- High temperature extensometers
- Tension/compression
- Force rating: 5-22kip



Melting & Processing

Mechanical Alloying



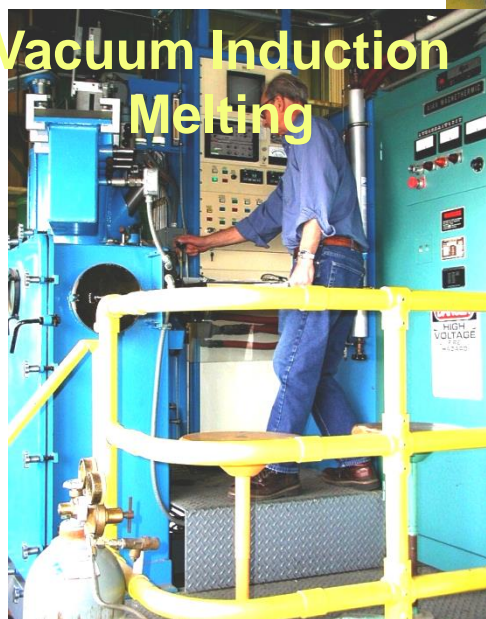
Welding and Joining



Vacuum Hot Press



Vacuum Induction Melting

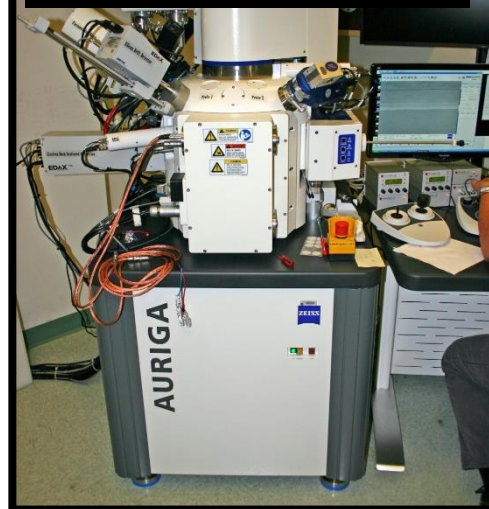


Analytical Sciences

Hitachi S4700-FESEM



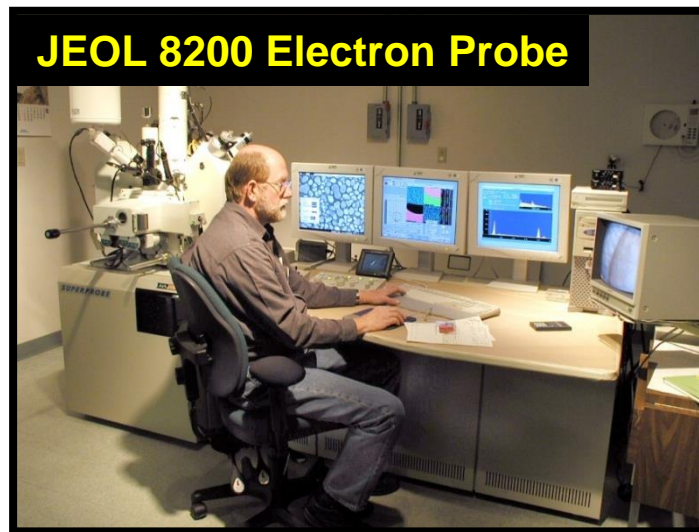
AURIGA™ Cross-Beam Microscope



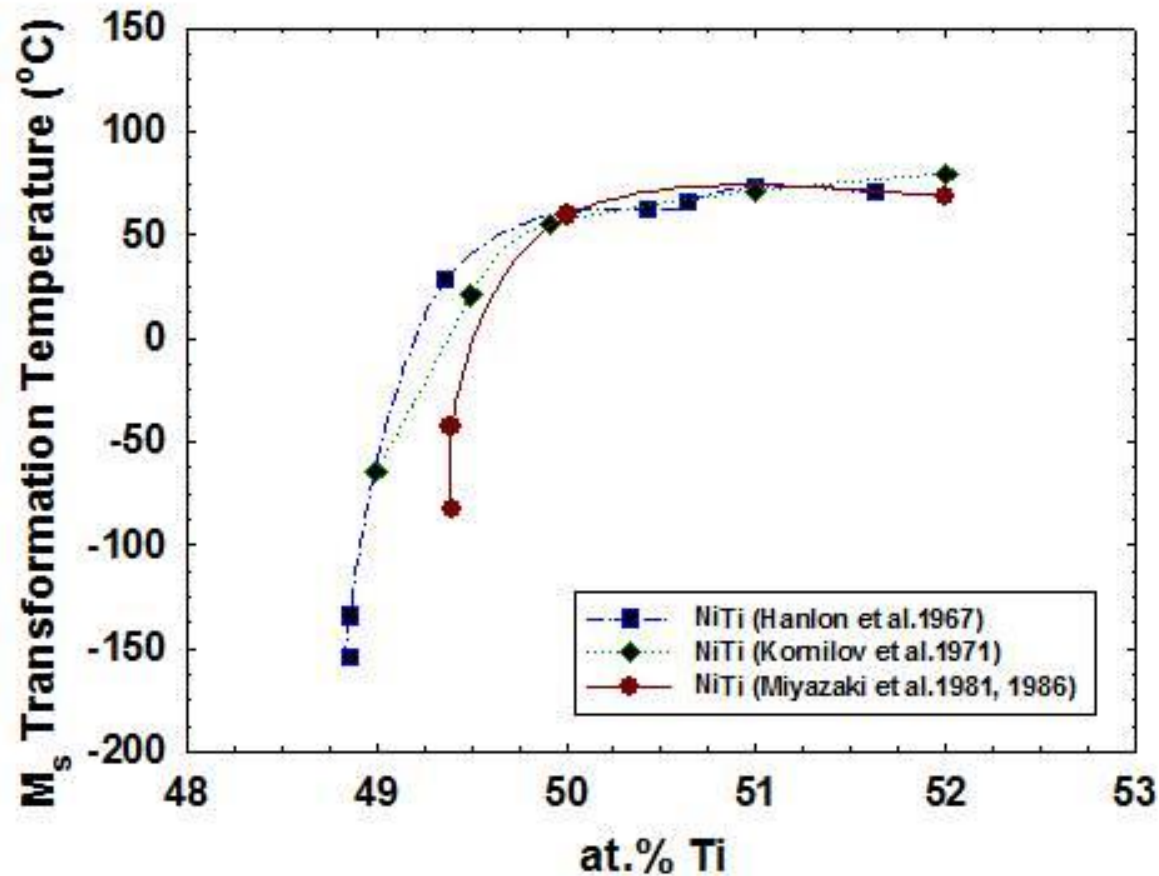
Philips CM200 TEM



JEOL 8200 Electron Probe



Development of Shape Memory Alloys: Challenges and Lessons Learned



Development of Shape Memory Alloys: Challenges and Lessons Learned

High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

Durability

- Loading history
- Functional fatigue
- Structural fatigue

Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

Workability/Processing

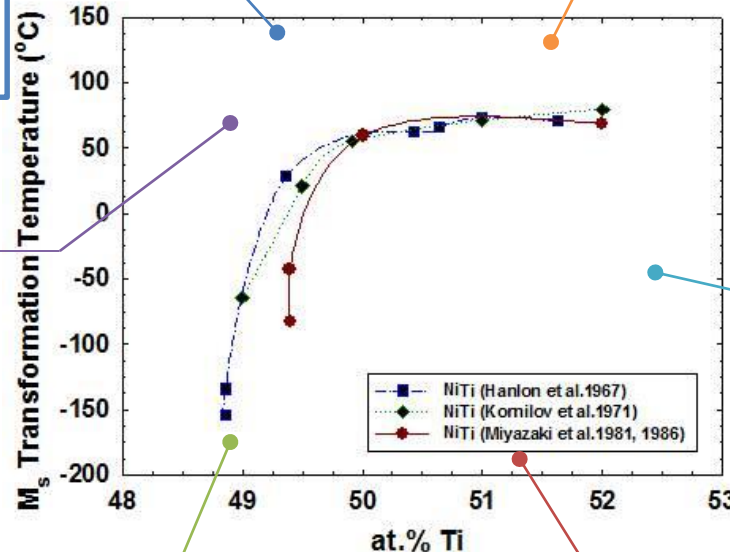
- Ductility
- Composition control
- Heat treatment

Dimensional stability

- Cyclic stability
- Stress-strain relationship

Certification

- Testing standards
- Material certification
- Database



55 Years after Nitinol Discovery

Metals

NiTi, NiTiFe, NiTiNb, NiTiCu, NiTiPd,
NiFeGa, NiTiCo CuZn, CuZnAl, CuAlNi,
CuAlNiMn, CuSn FePt, FeMnSi, FeNiC

AgCd
AuCd
CoNiAl

NiTiHf, NiTiZr, TiNiPd, TiNiPt,
ZrRh, ZrCu, ZrCu NiCo,
ZrCuNi CoTi, TiMo, TiNb,
TiTa, TiAu, UNb, TaRu, NbRu,
FeMnSi

Magnetic/Ferromagnetic

NiMnGa, FePd, NiMnAl,

FePt, Dy, Tb, LaSrCuO,
ReCu, NiMnIn, CoNiGa

Ceramics

ZrO₂ (PSZ), MgO,
CeO₂, PLZT, PNZST

PTFE, PU, Poly-caprolactone, EVA + nitrile
rubber, PE, Poly-cyclooctene, PCO– CPE blend

PCL–BA copolymer, Poly(ODVE)-co-BA,
EVA + CSM, PMMA,
Copolyesters, PET-PEG

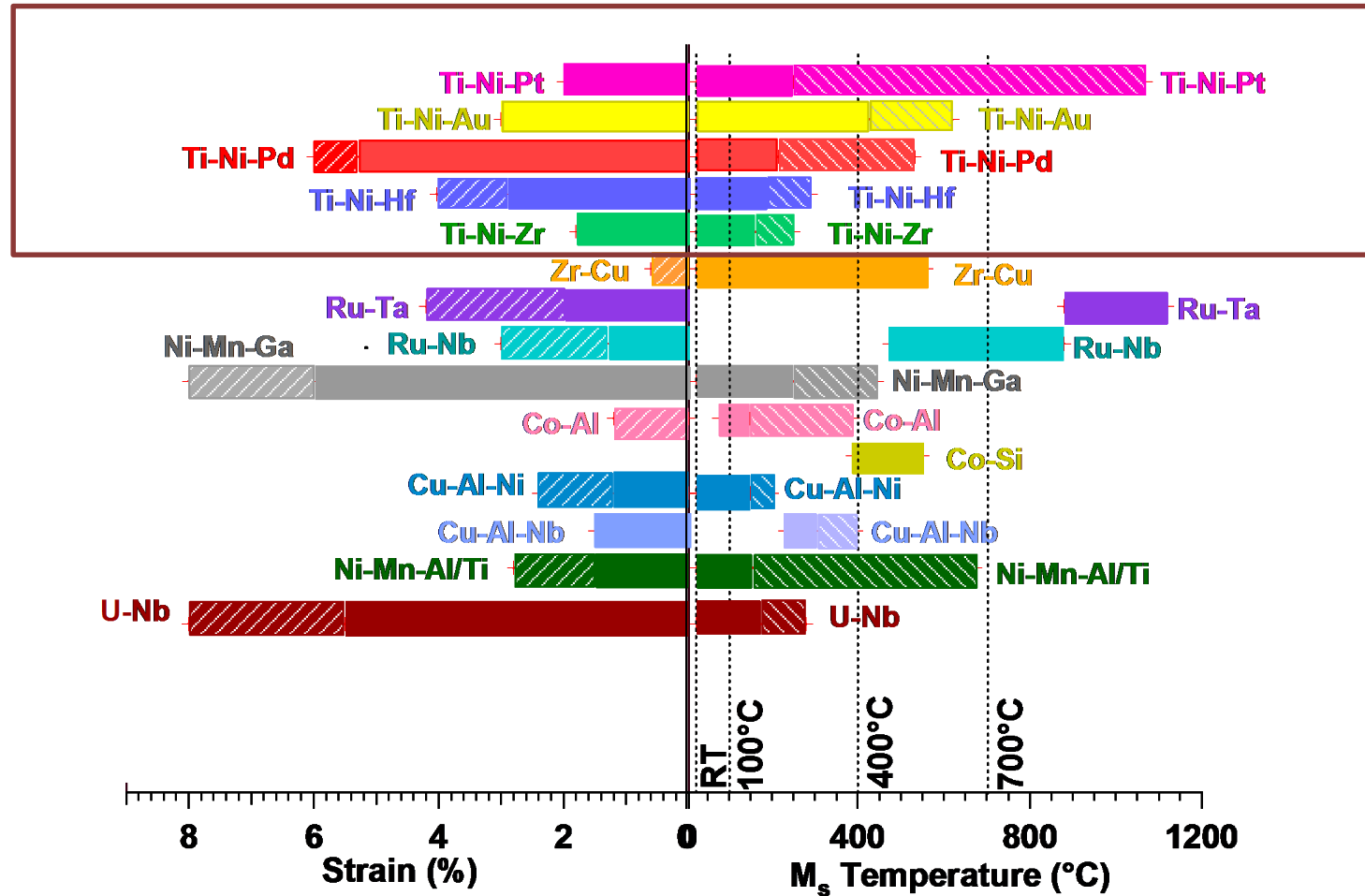
Polymers

Others

Thin films, hybrids...

Development of Shape Memory Alloys:

High Temperature Shape Memory Alloys (HTSMAs)

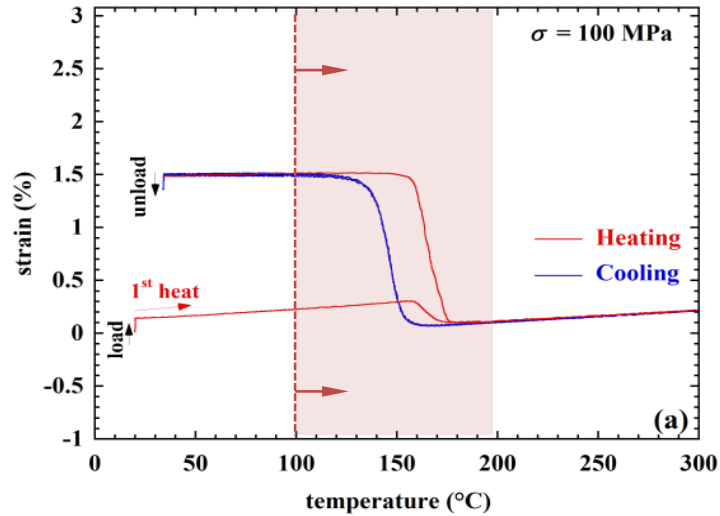


Ma et al. (2010)

Development of Shape Memory Alloys:

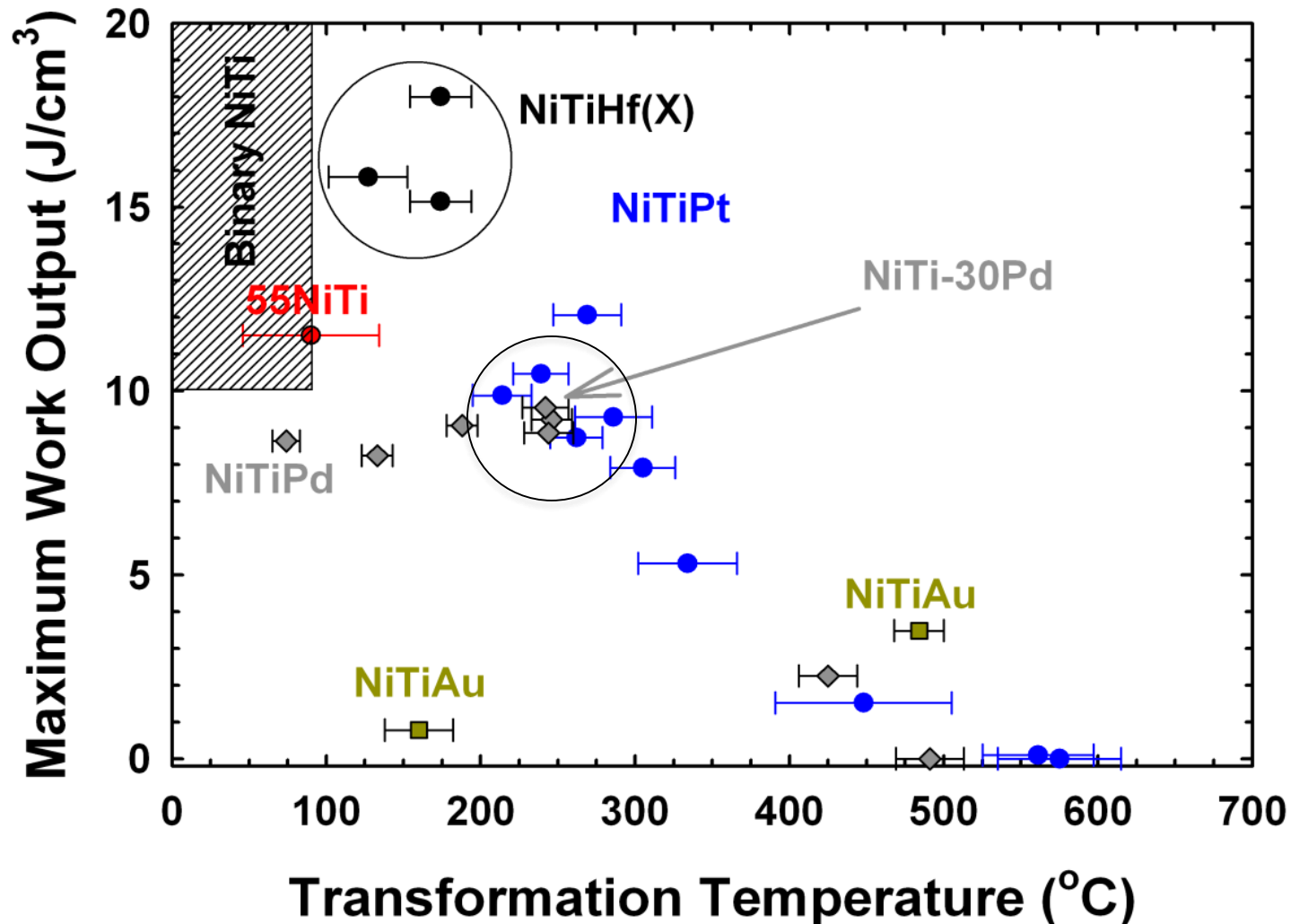
NiTi –Based HTSMAs

NiTiHf



Development of Shape Memory Alloys:

HTSMAs Summary



Development of Shape Memory Alloys: Challenges and Lessons Learned

High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

Durability

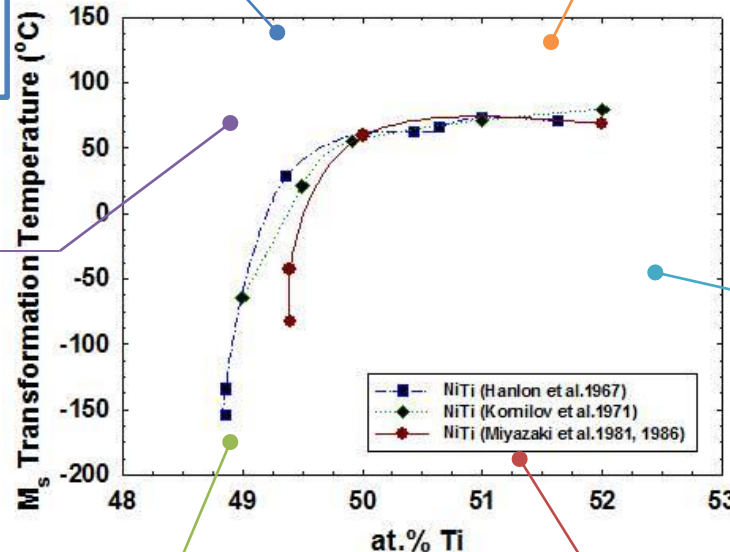
- Loading history
- Functional fatigue
- Structural fatigue

Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

Workability/Processing

- Ductility
- Composition control
- Heat treatment



Dimensional stability

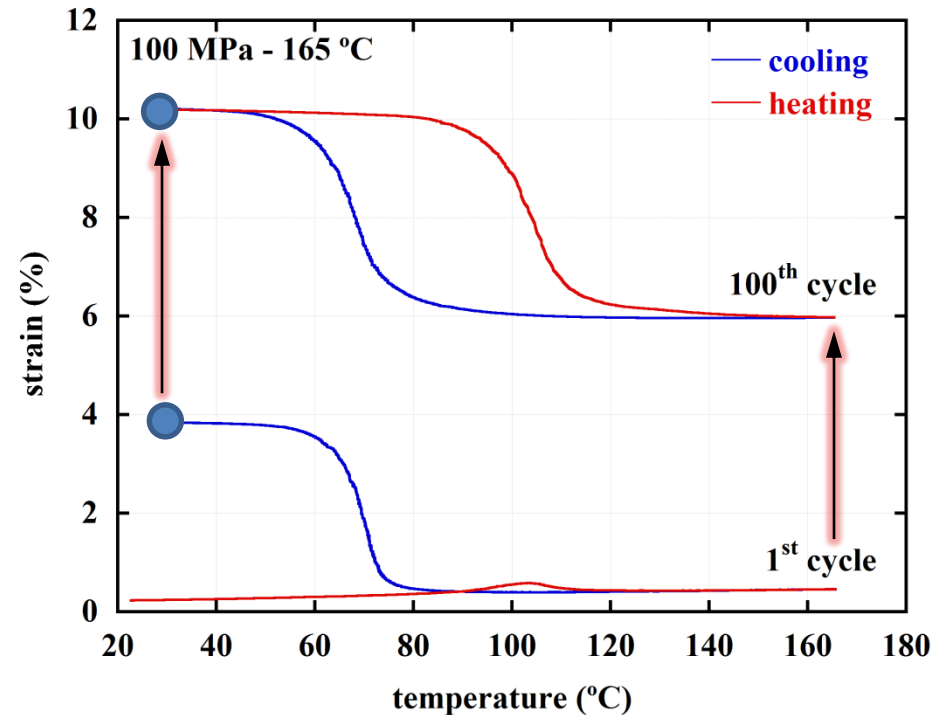
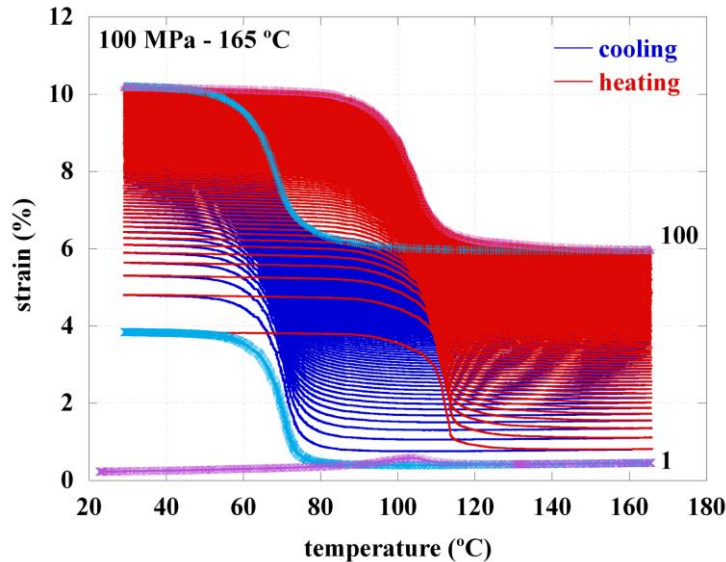
- Cyclic stability
- Stress-strain relationship

Certification

- Testing standards
- Material certification
- Database

Development of Shape Memory Alloys:

How about Dimensional Stability?

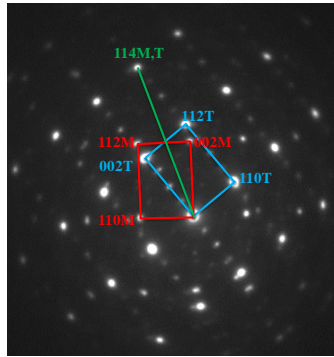
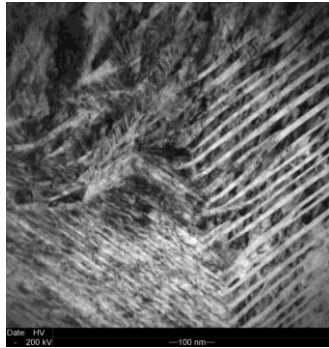


How to make the material/actuator stable?

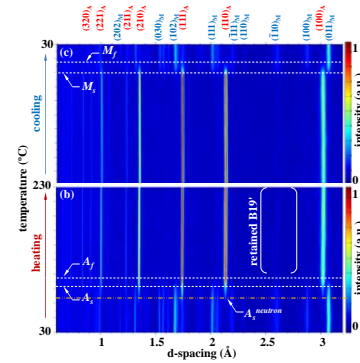
- Solution 1: Thermomechanical “training” (e.g., cycling, reverse loading...)
- **Solution 2: Alloying and microstructural control (e.g., precipitation hardening, Ni-content...)**

Microstructural Control towards Stability

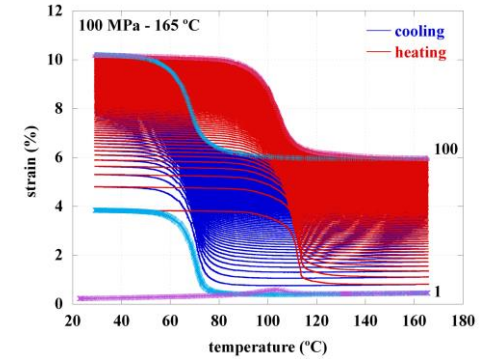
Electron diffraction



In situ diffraction



Outcome



Development of Shape Memory Alloys: Challenges and Lessons Learned

High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

Durability

- Loading history
- Functional fatigue
- Structural fatigue

Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

Workability/Processing

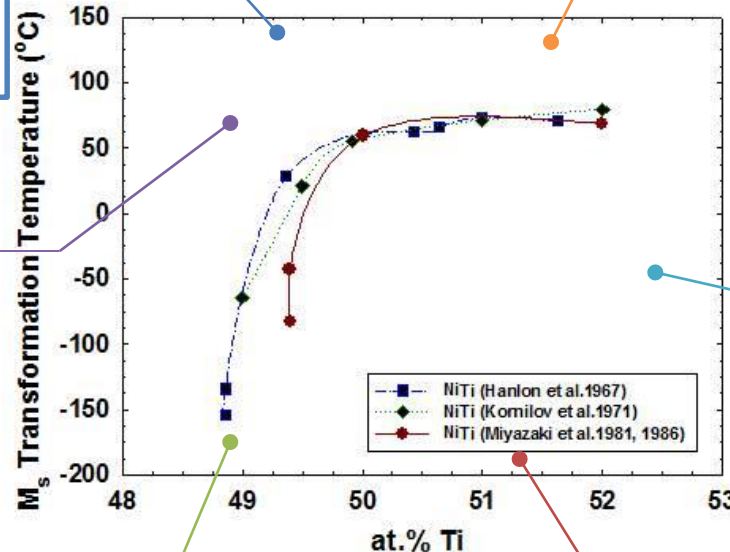
- Ductility
- Composition control
- Heat treatment

Dimensional stability

- Cyclic stability
- Stress-strain relationship

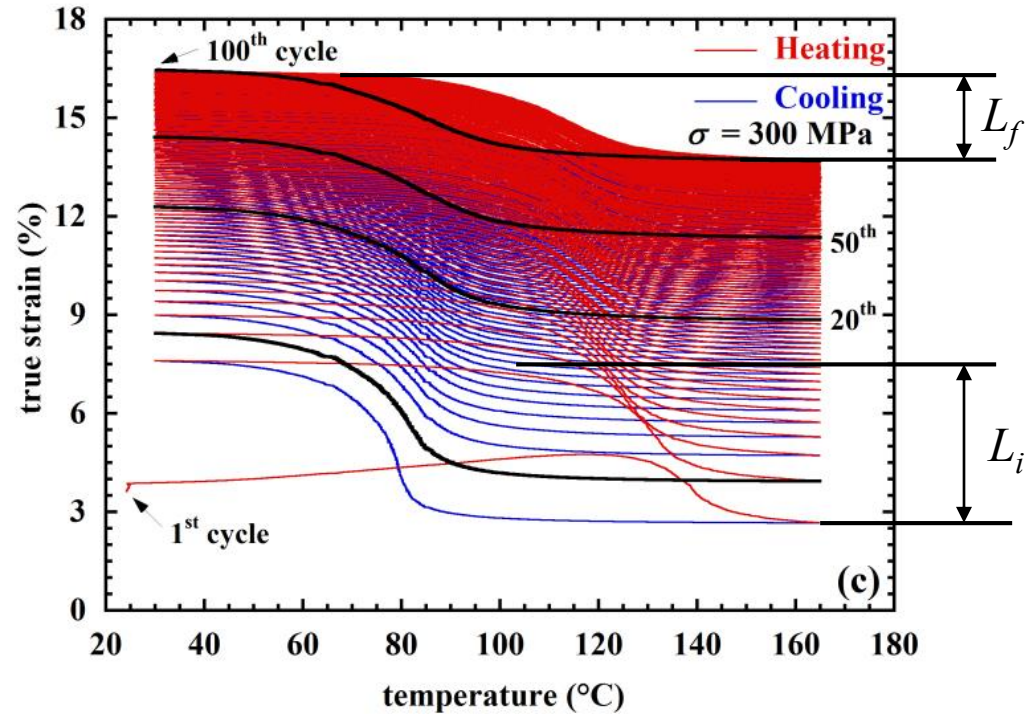
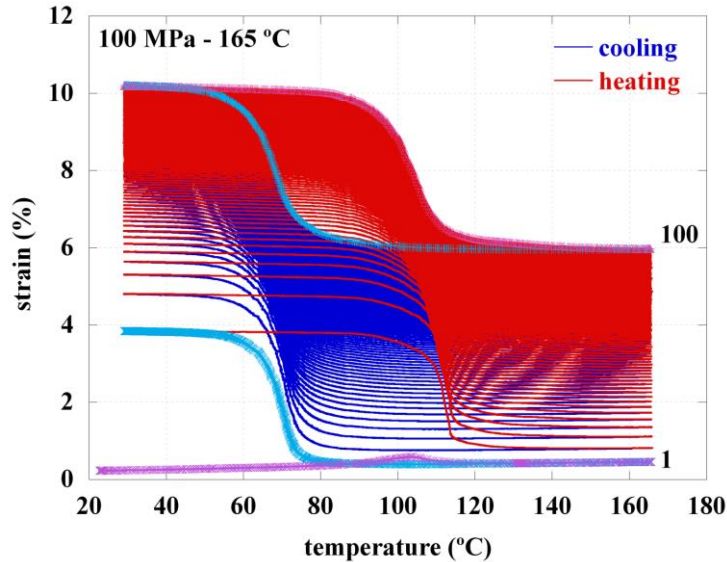
Certification

- Testing standards
- Material certification
- Database



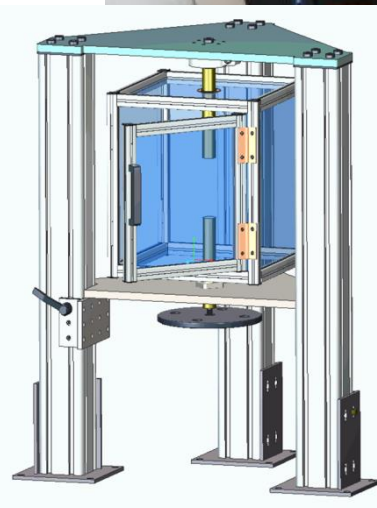
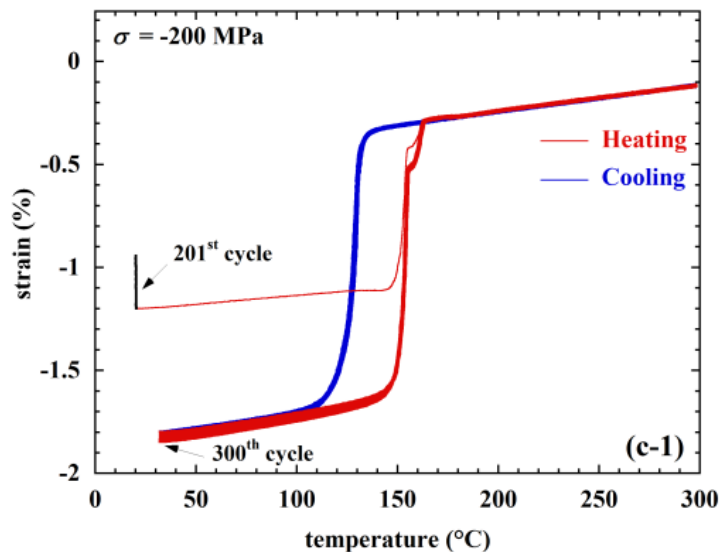
Development of Shape Memory Alloys:

How about Durability/Fatigue?



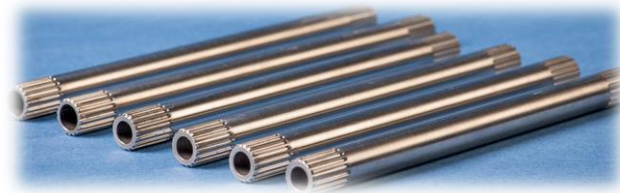
- Loss of actuation strain
- Shifts in transformation characteristics (Hysteresis, temperatures...)

Durability Assessment Underway...



Data exists up to 1000's of cycles, how about 1M cycles?

Currently collecting durability data on NiTiHf tubes

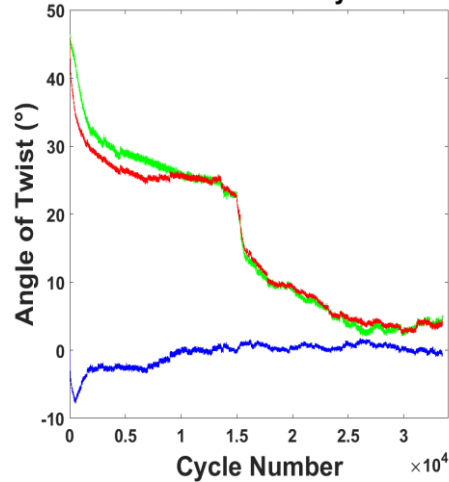


Durability Assessment Underway...

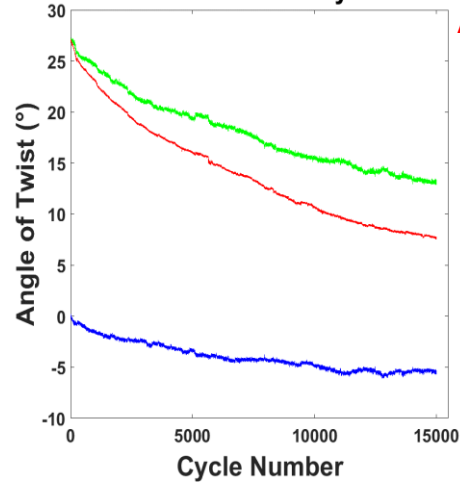
Austenite Angle - **Martensite Angle** = **Actuation Angle**

Strain Actuation $1/\alpha$ (Cycle Count \times MPa per load)

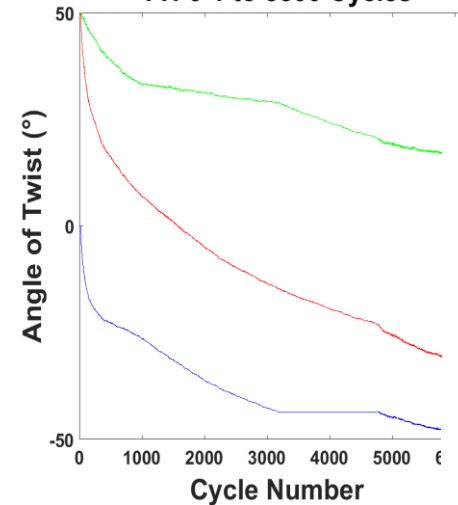
TTF1-1 to 33464 Cycles



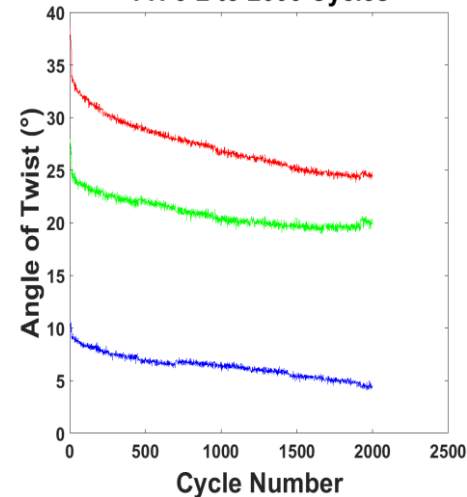
TTF2-1 to 15000 Cycles



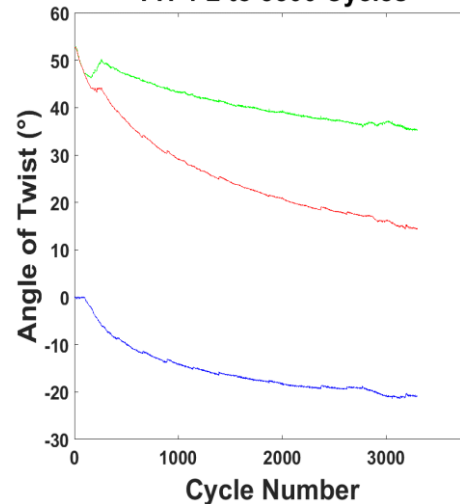
TTF6-1 to 5800 Cycles



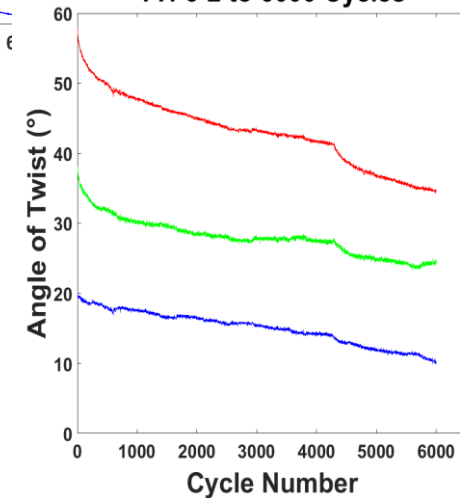
TTF3-2 to 2000 Cycles



TTF4-2 to 3300 Cycles



TTF6-2 to 6000 Cycles



Development of Shape Memory Alloys: Challenges and Lessons Learned

High transformation temperatures

- Above 100 °C
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- Thermal stability

Durability

- Loading history
- Functional fatigue
- Structural fatigue

Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

Workability/Processing

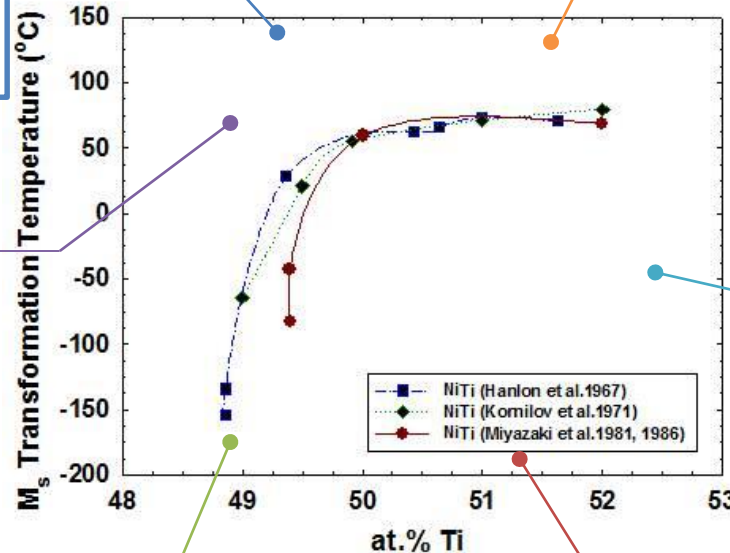
- Ductility
- Composition control
- Heat treatment

Dimensional stability

- Cyclic stability
- Stress-strain relationship

Certification

- Testing standards
- Material certification
- Database



Processing and Workability of HTSMAs

NiTiPt

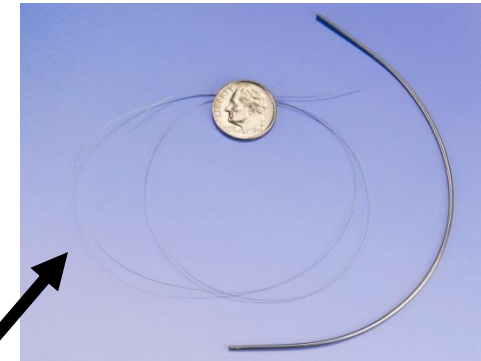
**Induction Melt
+
Homogenization**



Extrusion

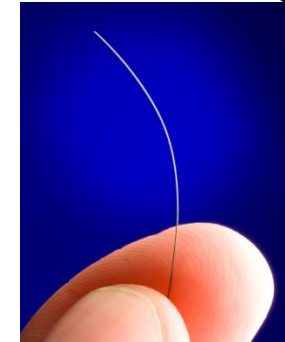


Wire Grinding



44 & 5 mil NiTiPt

Wire Drawing



5 mil NiTiPt wire

**Multiple-Pass Extrusion
60 mil NiTi-20Pt rod**

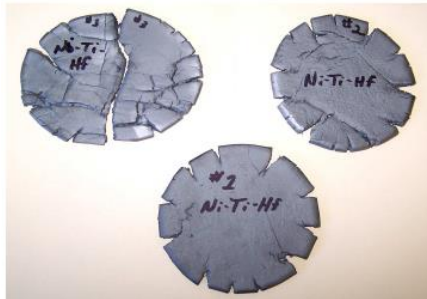


Processing and Workability of HTSMAs

NiTiHf



Successful hot rolled button (C. Wojcik 2008)



High temperature extrusion proved to be problematic (C. Wojcik 2008)



Successful hot extrusion (rods and tubes)

Development of Shape Memory Alloys: Challenges and Lessons Learned

High transformation temperatures

- Above 100 °C
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- Thermal stability

Durability

- Loading history
- Functional fatigue
- Structural fatigue

Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

Workability/Processing

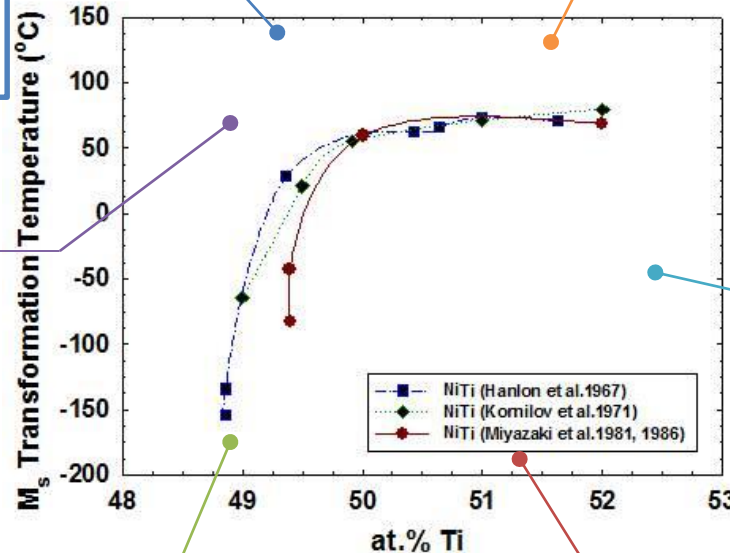
- Ductility
- Composition control
- Heat treatment

Dimensional stability

- Cyclic stability
- Stress-strain relationship

Certification

- Testing standards
- Material certification
- Database





Certification and Test Standards

ASTM Standards for biomedical and or superelastic

- F2004-05
- F2005-05
- F2063-05
- F2082-06
- F2516-07
- F2633-07

ASTM Standards for SMA Actuation

- **None**

Certification and Test Standards

ASTM Standards for biomedical and or superelastic

- F2004-05
- F2005-05
- F2063-05
- F2082-06
- F2516-07
- F2633-07



ASTM Standards for SMA Actuation

- **None**



Deliver the first ever regulatory agency-accepted material specification and test standards for shape memory alloys as employed as actuators for commercial and military aviation applications



Promoting Growth of SMA Technologies....



Development of Shape Memory Alloys: Challenges and Lessons Learned

High transformation temperatures

- Above 100 °C
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- Thermal stability

Durability

- Loading history
- Functional fatigue
- Structural fatigue

Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

Workability/Processing

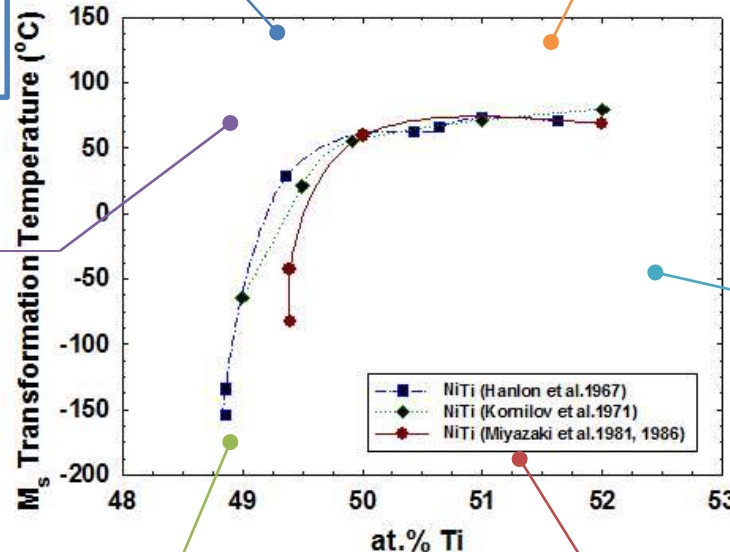
- Ductility
- Composition control
- Heat treatment

Dimensional stability

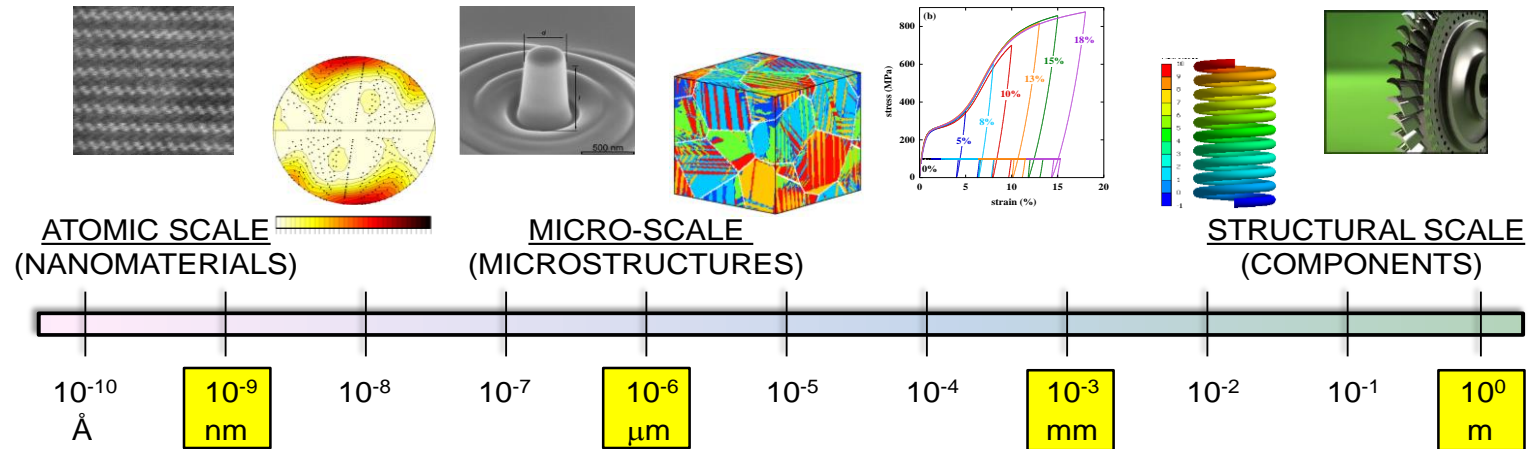
- Cyclic stability
- Stress-strain relationship

Certification

- Testing standards
- Material certification
- Database



Research and Understanding of Shape Memory Alloys

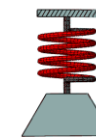
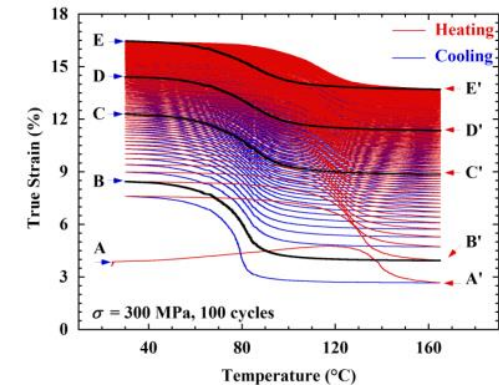
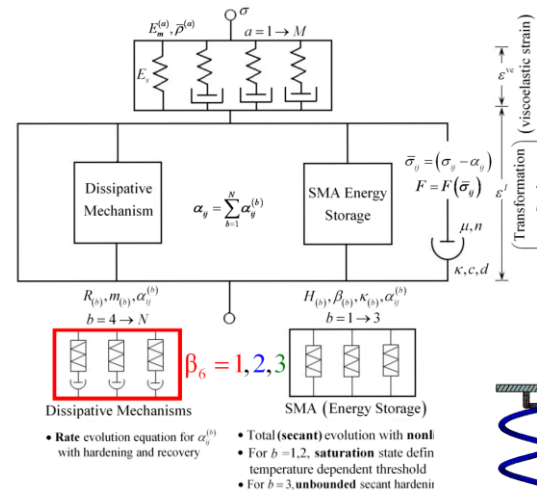


1. Applied Research

2. Alloy Processing & Development

3. Testing and Modeling

4. Applications

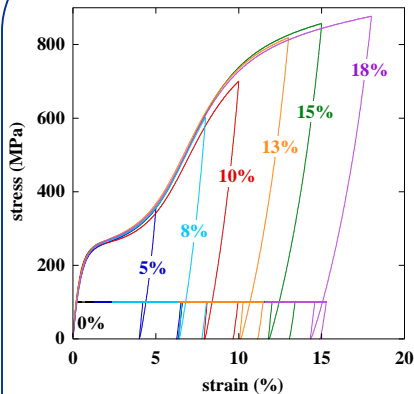




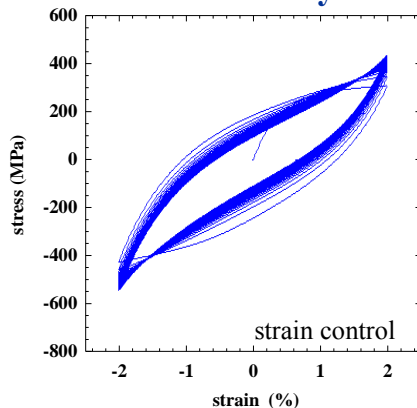
Complex Responses, Many Responses

Uniaxial (tension/compression)

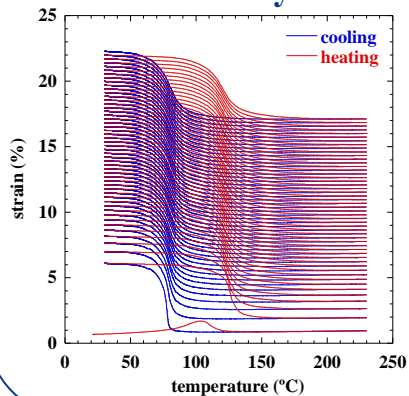
Isothermal monotonic



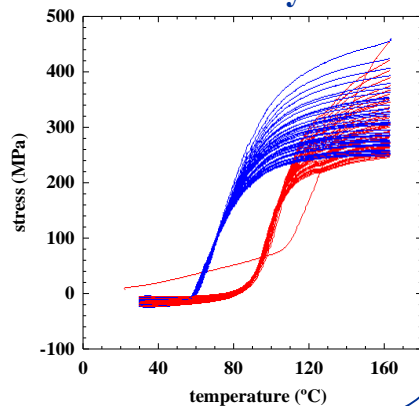
Isothermal cyclic



Isobaric cyclic



Isostrain cyclic



Durability

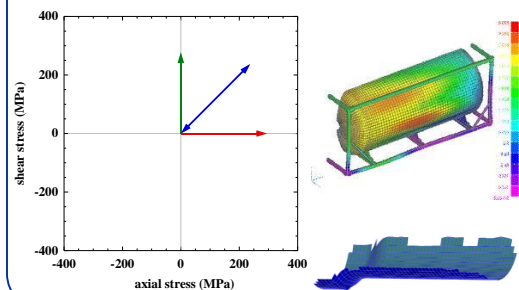
- New frames for durability testing are underway
 - Durability analysis of sample and components
 - Generate data for existing materials

Multiaxial

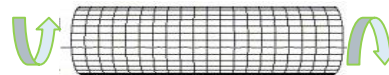
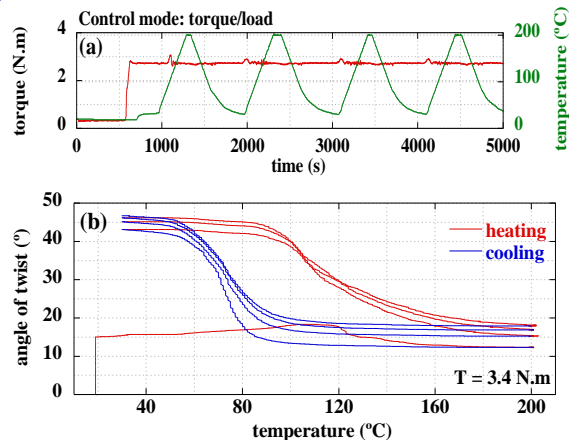
Geometries



- Proportional/non-proportional loading
- 3D strain measurement
- Torque/force/twist/displacement control capability



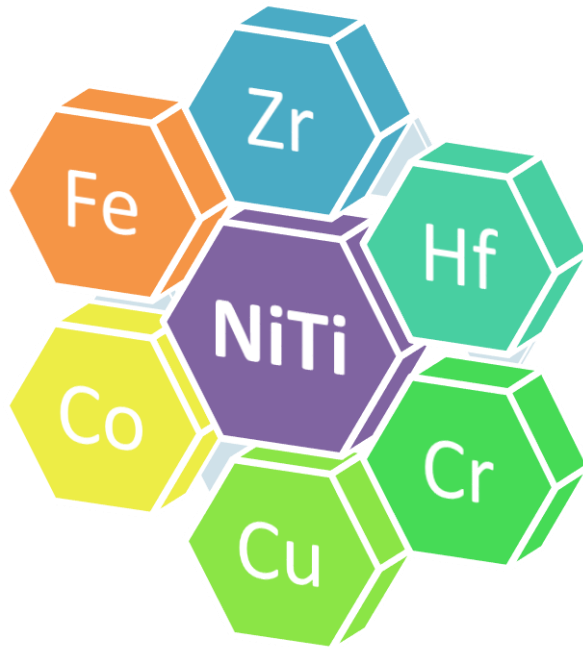
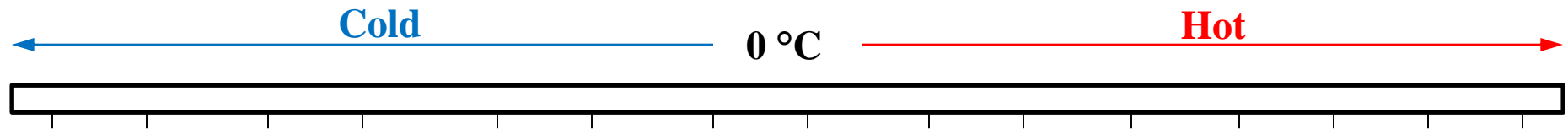
Torsion



Hot grip testing



Materials – High and Low Temperature SMA



Low Temperature SMAs

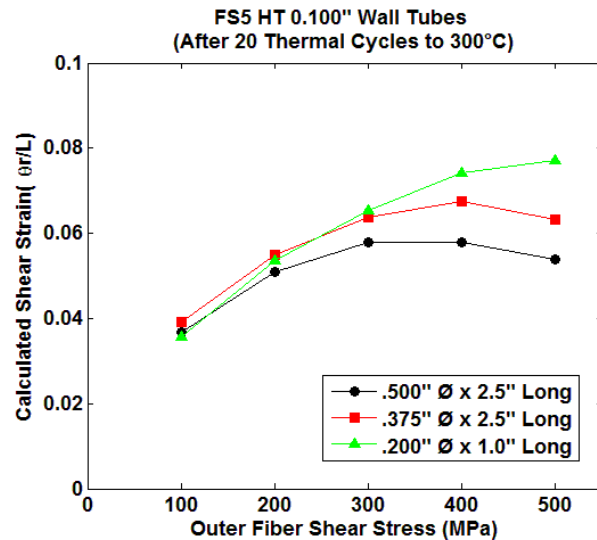
NiTi
NiTiFe
NiTiCo/Cr
NiTiCu
NiTiHf/Zr



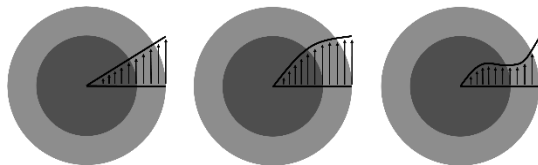
High Temperature SMAs

NiTiHf
NiTiZr
NiTiPd
NiTiPt
NiTiAu

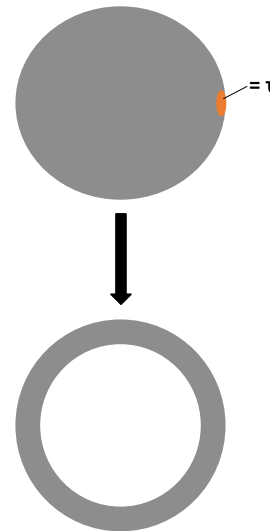
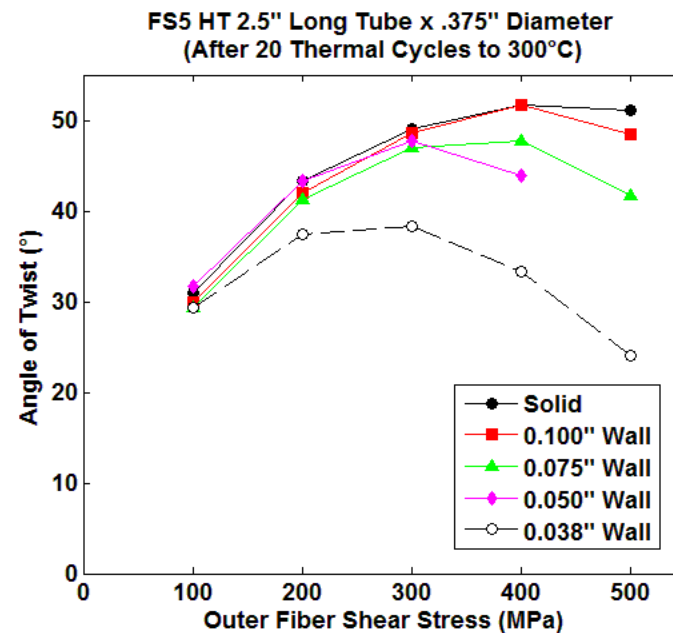
Design of Actuators- Torque tubes example



**Material and
geometry effects**

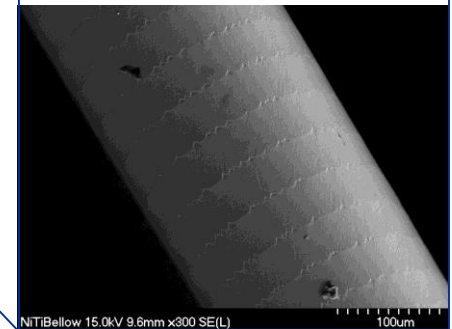
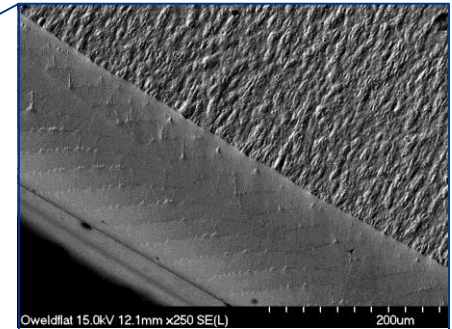
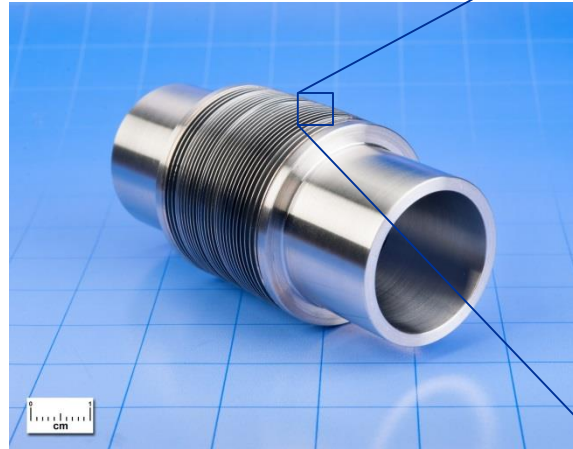
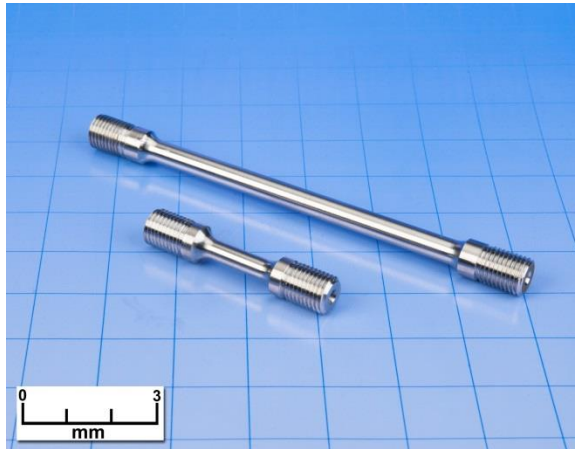


Possible Stress Gradients





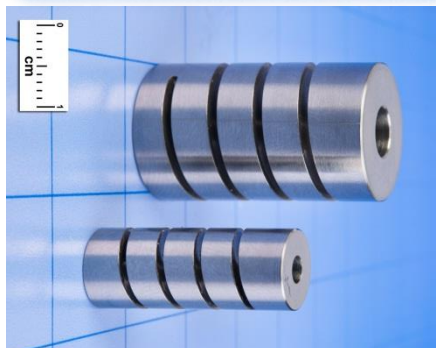
Some SMA Components



NASA C-2012-1098



National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field



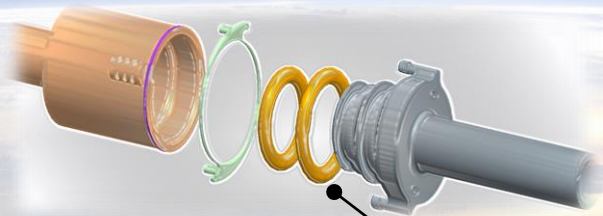
Shape Memory Alloy Applications

Space



SMA Bellows

- Dynamic sealing
- Fluid handling
- Flexibility (structure alignment)



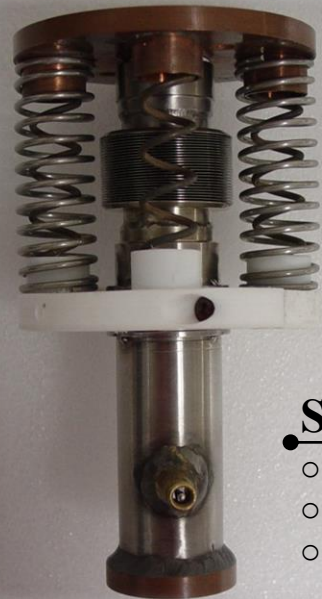
SMA Docking Coupling

- Cryogenic transfer coupling
- Orbital propellant depots
- Propellant handling/protection



SMA Spring Tire

- Superelastic technology
- Lunar rovers
- Terrestrial tires



SMA rock splitters



SMA Thermal Switch

- Thermal management
- Clean & spark-free operation
- Passive or active control



SMA Bearings

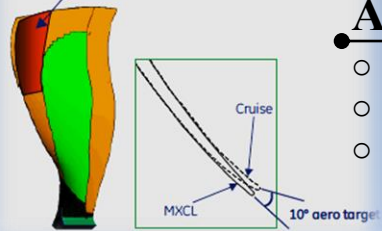
- Corrosion resistant
- Non-galling properties
- High yield

RXN

Shape Memory Alloy Applications

Aeronautics

Shape change region

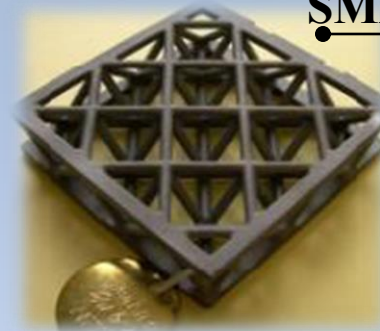


Adaptive Fan Blade

- Embedded SMA actuators
- Aerodynamic efficiency
- Specific fuel consumption reduction

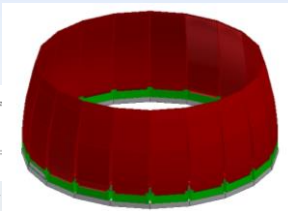
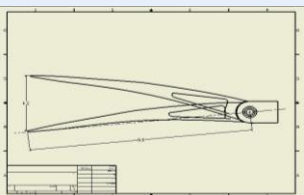
SMA Cellular Structures

- Airframe and engine components
- Morphing airfoils
- Light weight trusses



The Mars Atmosphere and Volatile Evolution (MAVEN) mission.

- SMA Pinpullers (From *TiNi Aerospace*) were used to secure and release deployables



Variable Area Nozzle

- High bypass turbofan
- SMA torque tubes provide flap rotation
- Engine noise reduction



Shape Memory Alloy Applications

Non-Aerospace Potential

Oil and Gas Industry

- SmartRAM™ actuators (*LMP*)
- SMA couplings (Aerofit Inc)
- Deep-water valves/shut off valves
- Self-torquing fasteners



Other Applications

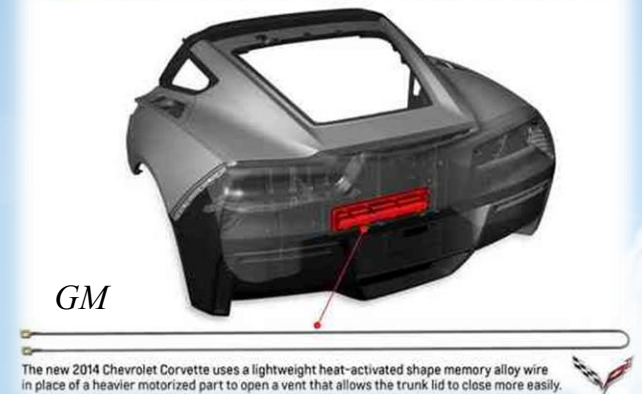
- Home appliances
- Electronics
- Transportation
- Air conditioners

Medical Industry

- Surgical tools
- Stents and implants
- Glasses frames



CORVETTE'S HEAT-ACTIVATED 'SMART MATERIAL'



Automotive Industry

- Louvers
- Quiet actuators
- Door handle



NASA SMA Team and Collaborators

SMA Team at NASA GRC

- Othmane Benafan
- Santo Padula II
- Glen Bigelow
- Anita Garg
- Darrell Gaydosh
- Timothy Halsmer
- Ron Noebe
- (Branch Chief: Joyce Dever)

Collaborators



Thank You

